

Observability of neutron events above the Greisen-Zatsepin-Kuzmin cut-off due to violation of Lorentz invariance

Nayantara Gupta ¹

*Institute of Mathematical Sciences,
C.I.T Campus, Taramani, Chennai 600113
INDIA.*

Abstract

The clustering of ultra high energy cosmic ray events suggests that they have originated from compact sources. One of the possible physical mechanisms by which ultra high energy nuclei reach the Earth from far away astrophysical sources (quasars or BL Lac objects) evading the Greisen-Zatsepin-Kuzmin (GZK) cut-off is by violation of Lorentz invariance. Assuming that there is violation of Lorentz invariance, we calculate the expected number of neutron events from some of the EGRET sources (including γ -ray loud BL Lac objects) which can be correlated in direction with ultra high energy cosmic ray events observed by AGASA above energy 4×10^{19} eV. We present in this paper what AGASA should see in future if violation of Lorentz invariance is responsible for the propagation of ultra high energy cosmic rays having energies above the GZK cut-off when there is a correlation of EGRET sources with the ultra high energy cosmic ray events.

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Observational data on ultra high energy cosmic ray events have been recorded by different experiments like Fly's Eye [1, 2], Akeno Giant Air Shower Array (AGASA) [3], Yakutsk experiment [4], Haverah Park [5], Volcano Ranch experiment [6] and Sydney University Giant Air-shower Recorder (SUGAR) [7]. The composition of the ultra high energy cosmic rays (UHECR) has been studied in [8, 10]. Data from Fly's Eye experiment [8] suggest that the chemical composition is dominated by heavy nuclei up to ankle ($10^{18.5}$) eV and thereafter by lighter component like protons. The AGASA data [10] suggest a mixed composition of both protons and heavier nuclei. The present experiments do not give us enough information about the chemical composition of primary UHECR. This topic has been addressed in [11]. If the UHECR are nuclei, then what could be their origin and how they propagate in the extragalactic

¹Email address: nayan@imsc.res.in

magnetic field are at present exciting fields of study. References [12, 13, 14] discuss different suggestions on these issues.

The Greisen-Zatsepin-Kuzmin(GZK) cut-off [15] will prevent nucleons of energy greater than 4×10^{19} eV from travelling more than about 50 Mpc, but most of the suitable astrophysical acceleration sites are located at greater distances. AGASA experiment [3] has recorded about 8 events above 10^{20} eV, whereas data recorded by HiRes fluorescence detector [16] seem to be in agreement with the GZK-cut-off [17]. Since currently the experimental data are not convincing enough for accepting the presence of the GZK cut-off, theoretical suggestions for observability of cosmic rays above the GZK cut-off remain of interest to us. The Physics involving the formation and annihilation of topological defects (TDs) has been studied as a possible explanation of observing UHECR. However TD annihilation has unique observational consequences such as, copious production of particles like neutrinos and γ -rays [18]. The experimental signatures of the Z-burst scenario has been discussed in [19]. Gamma ray bursts have also been identified as a possible explanation of observing UHECR above the GZK cut-off [20, 21].

If the highest energy cosmic rays have a neutral component then that will come to the Earth from the direction of its source. Elbert and Sommers [22] identified radio-loud quasar 3C147 as an ideal source within 10° of the highest energy event observed by Fly's Eye experiment [1] at energy 3.2×10^{20} eV. Later another quasar PG0117 + 213 was identified by Biermann [23] within the error cone of the second highest energy event observed by AGASA [24]. In the last few years a lot of work has been done by different groups [25, 26, 27, 28] in correlating UHECR events with radio quasars and BL Lac objects. It was pointed out by Dubovsky et al. [29] that the statistics of clustering of ultra high energy cosmic ray events suggests their correlation with compact sources. In [30] the authors have pointed out that there is no significant correlation between quasars or BL Lac objects and ultra high energy cosmic ray events. They have used data from Haverah Park [5] and Volcano Ranch experiments [6] for their statistical analysis. However, the authors of [26] have shown that there is a significant correlation between compact sources and observed ultra high energy cosmic ray events using the data from AGASA [3] and Yakutsk [4] experiments. The probability of positional coincidence between BL Lac objects and UHECR events to occur by chance in a random distribution is of the order of 10^{-4} . The still unknown data from HiRes experiment [2] and the accumulating data from AUGER experiment [31] will enable us to carry out statistical analysis with a bigger set of data in the near future.

Since, as of now it is not clear whether the UHECR events are statistically uncorrelated with compact sources at high redshifts, the physical mechanisms by which

neutral component of UHECR may come to the Earth evading the GZK cut-off from high redshifts are still exciting fields of study for us. In the Z-burst scenario [32] or in models of hypothetical “immune messengers” [33] neutral particles can come to the Earth from the direction of the source evading the GZK cut-off. It has been suggested by Coleman and Glashow [34] that if there is violation of Lorentz invariance (VLI) then protons and neutrons of energies above the GZK cut-off will reach the Earth without interacting with the cosmic microwave background. In the present work we show that one can test whether VLI is responsible for the observability of the UHECR events above the GZK cut-off using the data from AGASA experiment and certainly with the data from AUGER [31] experiment in future. We have predicted what AGASA should see in future if VLI is the underlying physical mechanism for propagation of cosmic rays with energies above the GZK cut-off from compact sources at high redshifts.

We consider the ultra high energy cosmic ray events observed by AGASA above the GZK cut-off. Among this set of events we find that some of them can be correlated in direction with EGRET sources from the third EGRET catalog [36]. In [27] the authors have suggested that the sources of UHECR are high energy peaked BL Lac objects. Our set of correlated EGRET sources also include γ -ray loud BL Lac objects. If the radiation energy density is sufficiently high in a source, photo-pion production leads to the generation of a sufficient number of neutrons which can escape from the system. If there is VLI the neutrons having an energy above a certain energy will not decay. The energy above which the neutrons become stable depends on the degree of VLI. In [35] the authors have obtained a limit on the energy above which neutrons become stable, using observational data from the Yakutsk experiment [4]. These neutrons can travel through the cosmic microwave background with energy above the GZK cut-off when there is VLI and in that case we expect to detect them from the direction of the compact source. For clusters of UHECR events we consider sources within 4° of the events and for a single event we correlate with a source within 2.5° . In our correlated data set we have eight EGRET sources, among which three (3EG J0433+2908, 3EG J1052+5718 and 3EG J1424+3734) are confirmed BL Lac objects from the Véron 2001 catalog [37, 27]. Among the remaining five, 3EG J1744-0310 is a quasar [38]. The four unidentified EGRET sources i.e. 3EG J1824+3441, 3EG J1903+0550, 3EG J0429+0337 and 3EG J0215+1123 may be BL Lac objects that have not yet been confirmed. Two of these four unidentified EGRET sources are also present in Table 3 of [27].

TABLE I. The EGRET sources correlated with UHECR events above 4×10^{19} eV in AGASA data

3EG J	EGRET ID	Type of Object	l_s (deg)	b_s (deg)	z	l (deg)	b (deg)	E 10^{19}eV
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
0433+2908	AGN	BL Lac	170.5	-12.6	> 0.3	170.4	-11.2	5.47
		2EG J0432+2910						
						171.1	-10.8	4.89
1052+5718	Possible AGN	BL Lac	149.6	54.42	0.144	147.5	56.2	5.35
		RGB J1058+564						
						145.5	55.1	7.76
1424+3734		BL Lac	63.95	66.92	0.564	68.5	69.1	4.97
		TEX 1428+370						
1744-0310	AGN	Quasar	22.19	13.42	1.054	22.8	15.7	4.27
0215+1123			153.75	-46.37		152.9	-43.9	4.2
0429+0337			191.4	-29.08		191.3	-26.5	6.19
1824+3441			62.49	20.14		63.5	19.4	9.79
1903+0550			39.52	-0.05		39.9	-2.1	7.53

In the first row of TABLE I we note that the redshift of the EGRET source 3EG J0433+2908 is more than 0.3 [39]. The fourth and fifth columns of TABLE I give longitudes and latitudes of the sources in Galactic coordinates and the seventh and eighth columns display longitudes and latitudes of the UHECR events in Galactic coordinates.

We consider the sources of TABLE I whose redshifts are known and calculate the number of neutron events from them expected to be detected by AGASA in 30 years. We calculate the expected number of neutron events from the source 3EG J0433+2908 assuming its redshift to be 0.3. In future we will come to know the redshifts of the other EGRET sources and then it will also be possible to calculate the expected number of neutron events from them. There are both theoretical [40] and observational [41] reasons to believe that when proton acceleration is being limited by energy losses, the luminosity of the object in very high energy cosmic rays L_{CR} is approximately equal to its luminosity in gamma rays. The cosmic ray luminosity L_{CR} in the energy range $1 \times 10^{19} \text{eV} < E < 4 \times 10^{20} \text{eV}$ can be assumed to be emitted equally in each decade of energy E . In that case, in each decade of energy we expect the power emitted in UHECR in the energy range of $1 \times 10^{19} \text{eV}$ to $4 \times 10^{20} \text{eV}$ to be approximately $L_{CR}/10$. Let ‘ A ’ be the area of AGASA detector which is 10^{12}cm^2 [3]. Here we mention that the exposure of the AGASA detector is energy independent in

the energy range in which we are interested. One can see the plot of exposure against energy of the UHECRs for AGASA detector in [42]. The expected number of neutron events in a time interval dt_o in AGASA within the source energy interval of E_1 and E_2 can be expressed as

$$\frac{dN_o^n}{dt_o} = \frac{A}{4\pi d^2} \int_{E_1}^{E_2} \frac{dN_s^n}{dE_s dt_s} dE_s \quad (1)$$

where d is the luminosity distance of the source from the Earth. N_s^n and N_o^n are respectively the number of neutrons emitted at the source and observed by the detector. E_s , E_o are the source energy and observed energy of the neutrons respectively. If the redshift of the source is z then $E_o = E_s/(1+z)$. Similarly the correction to be applied to observed time t_o due to redshift of the source is $t_o = t_s(1+z)$, where t_s is the time at which the neutron is emitted from the source.

We have assumed there is VLI and that the lower limit of the above integration is such that neutrons are stable above this energy.

We define F_γ^{ob} as the energy received in gamma rays per second per cm^2 on the surface of the Earth from an EGRET source and this quantity can be calculated from [36]. ϵ_n is the efficiency of neutron production in the source. When the photon density in a source is sufficiently high then the efficiency of neutron and proton production become comparable near the end of the UHECR spectrum [43]. Hence it is not unreasonable to assume $\epsilon_n = 1/2$ in our calculation. If we assume the luminosity of the source in gamma rays of energy more than 100MeV L_γ to be a fraction x times the luminosity of the source in UHECR L_{CR} , then eqn.(1) can be written as

$$\frac{dN_o^n}{dt_o} = A\epsilon_n x \frac{F_\gamma^{ob}}{10} \int_{E_1}^{E_2} \frac{dE_s}{E_s^2} \quad (2)$$

An almost similar procedure has been followed in ref.[43] in calculating number of neutron events from Centaurus A but without the assumption of VLI. Using eqn.(2) we calculate the expected number of neutron events between observed energy intervals of 1×10^{20} eV and 2×10^{20} eV in AGASA from the sources of TABLE I whose redshifts are known. The second column of TABLE II displays the photon flux in 10^{-8} photon $cm^{-2}sec^{-1}$ above 100 MeV energy for the EGRET sources in the first column [36]. The third column shows the photon spectral indices from [36] of the EGRET sources displayed in the first column. The fourth and fifth columns present the expected number of neutron events in a time interval of 30 years in AGASA for case (1) $\epsilon_n = 1/2$, $x = 1$ and for case(2) $\epsilon_n = 1/2$, $x = 1/2$ respectively.

TABLE II. The number of neutron events between energy 1×10^{20} eV and 2×10^{20} eV expected in AGASA in 30 years from some of the EGRET sources of TABLE I.

3EG J	Photon flux above 100 MeV	Photon Spectral Index	Number of Neutron Events in case (1)	Number of Neutron Events in case (2)
0433+2908	22.0	1.9	8.4	4.2
1052+5718	6.5	2.51	2.2	1.1
1424+3734	16.3	3.25	3.5	1.7
1744-0310	21.9	2.42	4.29	2.1

In the last 10 years data from AGASA there is no event above 10^{20} eV energy from the direction of the sources of first column of TABLE II. If VLI is the underlying mechanism for UHECR propagation then we can expect to see UHECR events above 10^{20} eV from the direction of the sources presented in TABLE II in future. If we increase the area of the detector or the time of data collection then of course we would detect more neutron events than that presented in TABLE II. The number of neutron events will increase linearly with increasing area or time of data collection by the detector. Since the area of AUGER is 30 times larger than AGASA, we can expect such neutron events in a much shorter interval of time in AUGER.

Conclusion

In this paper we have presented how the UHECR data above the GZK cut-off can tell us whether VLI is the underlying mechanism for the propagation of these cosmic rays from quasars or BL Lac objects at high redshifts.

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